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PERFORMANCE DATA AND PROPOSED NEW DESIGN FOR A VISION SYSTEM FOR MOBILE ROBOTS

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INTRODUCTION

A vehicle intended for use on the planet Mars, and therefore capable of autonomous operation over very rough terrain, has been under development at Rensselaer Polytechnic Institute since 1967. Early efforts were directed chiefly toward deployment, structural, and suspension problems, and resulted in a storage-battery-powered vehicle that served as a test bed for later developments. The next phase consisted of the development of a primitive vision system for detecting obstacles. This consisted of a pulsed solid state laser source and a single photodetector with lens both mounted on the same mast. As the mast is rotated, they scan the terrain ahead at a fixed elevation angle such that a ground reflection should be received for relatively flat terrain. Azimuth angles for which no ground reflection is received are presumed to contain boulders or craters. This information is processed and used to guide the vehicle by means of telemetry and a remote computer. A vehicle using this system was successfully tested in 1978. The results are summarized in Report MP-61 [1].

Despite the success of the 1978 vehicle, it was apparent from our experience with it that in real situations involving near extremes of pitch and roll capability, the single elevation angle available was too restrictive. Therefore a multi-laser multi-detector (ML/MD) system was already under development in 1978. This more sophisticated vision system continues to use triangulation as a basic feature, but scans the terrain ahead in two dimensions. It is capable of placing up to 1024 points of laser light on the terrain with each azimuth scan as compared to 15 points in the earlier system.

Many of the implementation details of the ML/MD system were considerably more complex than those of the early simple arrangement, and the system generated data at a much higher rate, requiring a redesign of the telemetry system, and new terrain modeler programs. A decision was also made at about the same time to implement a digital, rather than analog motor drive method for the wheels. A move to a new building also seemed to be an appropriate time to begin use of a newly available more-modern computer. In addition, there was a gradual realization that many features of the practical evaluation of a vision system did not require a vehicle and real terrain, but could be accomplished in a laboratory with "artificial terrain" placed in the vicinity of a fixed position vision system, especially if the attitude of the vision system could be adjusted to simulate vehicular pitch and roll.

Along with the increased complexity of many of the major systems both on and supporting the vehicle, there was an additional problem - a gradual reduction to near zero of the funding level. Therefore, in 1981 we had a vehicle with many new systems, none of which had been extensively tested. At the same time, DARPA was interested in acquiring a vision system suitable for a projected adaptive suspension vehicle that would operate on earth, but over very rough terrain, and we agreed to spend 1982 in an attempt to obtain detailed performance data on the ML/MD vision system in the laboratory, and to try to design a similar system with improved range and resolution capabilities.

THE ML/MD SYSTEM

The ML/MD system is based on a continuously rotating mast, with electrical connections through slip-rings. Near the top there is a solid state pulsed laser directed vertically, with a single lens to help confine the beam. At the very top there is a rotating eight-sided mirror. Both the mirror and mast angular position are known by means of coupled shaft angle encoders. The system produces a laser pulse at each of 32 elevation angles ranging from 23° to 56° (from vertical) for each of 32 azimuth angles from directly ahead to 43.5° to each side. The laser strikes level ground roughly 1 to 3 meters in front of the mast. A complete scan takes about half a second, and the mast takes about 2 seconds per revolution.

About a meter below the top, there is mounted on the mast a 35 mm camera lens. In back of the lens, near the normal film position, there is located a linear array of 20 photodiodes, about 20 mm long, and disposed vertically. For each laser pulse, one or more of the diodes is illuminated with reflected light, and this information can be analyzed to produce a rough map of the terrain in the region scanned. The resolution of the detection system is approximately 1.5°. More detailed technical information about hardware aspects of this system is available in references [2],[3], [4], and [5]. References [5] and [6] include overviews along with some error analyses of the triangulation method.

ML/MD PERFORMANCE

Performance testing of the ML/MD system was accomplished using the rotating mast mounted on a platform. The platform could be adjusted so as to produce a variety of apparent pitch and roll angles, but most data was taken for the level platform case. The platform put the mast at a height such that the actual floor of the room is 34.5 cm below the ground level plane designated as zero by the triangulation system. In this way, artificial barriers (cardboard cartons) placed in the field of view could produce apparent terrain ranging from 34.5 cm. below to a nearly unlimited height above the zero plane. An appropriate software program enables the apparent location of obstacles to be visualized on a monitor screen.

The testing was done using the following sequence. First, a single rectangular step was placed at 1 meter ahead of the mast, and its height varied in 5 cm. increments. A slope test was then performed using a 183 cm. by 66 cm. ramp, starting at 1 m ahead of the mast. The angle of the ramp was varied from 5° to 40° in 7 equal steps. The azimuth resolution was then tested by placing two similar obstacles next to each other and gradually changing the height of one of them. Two similar obstacles with varying distance between them, to simulate a narrow pass between two cliffs, were also studied. Ranging tests used a single 30 cm. by 30 cm. obstacle at distances in 10 cm. steps from 40 to 230 cm. The next sequence involved an array of cartons with one missing to simulate a hole. The hole depth was varied systematically for several sizes of rectangular hole.

Some preliminary results of a few of these tests appear in reference [6], but the bulk of the test results are detailed in [7], mostly in the form of computer generated terrain maps showing numbers where the hazards are detected, along with a code designating the type hazard associated with each number displayed.

In a general and approximate way, the results may be summarized as follows. Barriers that were 25 cm. high, the value designated as possibly hazardous to this vehicle, were always detected (at 1 m distance), but 20 cm. high barriers were not. Height values were within a few cm. of actual heights. Cross-step hazards were reliably detected. Range information proved to have a consistent error of unknown cause of about 5 cm. Slope hazards were not reliably detected, but this is likely to be caused by a modeler program problem, rather than an inherent difficulty with the triangulation method. The useful range resolution was only about two meters on level ground, just about adequate for the low speed rover.

PROPOSED EXTENDED RANGE SYSTEM

The adaptive suspension vehicle, on earth, faces many requirements for its vision system different from those for the Mars rover. The color, texture, and crushability of the ground cover on earth may well be due to vegetation rather than minerals. (These problems were not addressed, however.) Tree trunks and low branches are real obstacles here. Higher vehicle speeds are also needed. A tentative design for a vision system based on our experience with the rover, but permitting increased range and resolution, was developed during 1982 and early 1983. It is fully described in reference [8], but its main features will be outlined as follows.

One special advantage of the new system design that was sought but not fully accomplished was to replace the rotating mast structure with components having no moving parts. The pulsed laser light source can be deflected by solid-state electro-optic devices, but in the present state of the art, these devices pass too little light to be useful in this application for the deflections required. Instead, a set of grating holograms around the perimeter of a rotating disk is proposed to deflect the beam in elevation by diffraction. Such a scheme is in use for bar-code scanners, and is much more tolerant of shaft wobble and has lower inertia and wind loss than a rotating multi-faceted mirror. Its light losses are only slightly higher than those of mirrors. The lower speed scanning for azimuth deflection will be done by a galvanometer actuated mirror. The transmitting module need not be directly above the receiver, and could well be mounted on the roof of the vehicle.

The receive module should be mounted at the front of the vehicle and lower than the transmitter. It need not have moving parts if appropriate cylindrical lenses are used, so that the entire field of view is condensed onto a thin vertical line. Alternatively, another galvanometer actuated mirror could be used for the azimuth scan, with spherical lenses or mirrors. Some of the electronic difficulties involved in the wideband amplification of the small light pulses from the photodiode linear array can be avoided by using an array of optical fibers, each leading to its own wideband detector-amplifier. This should increase the detector sensitivity by at least two orders of magnitude. (Two-dimensional arrays of photodetectors would require no azimuth scan, but are currently unavailable in a form with sufficient dynamic range and low noise unless each element is separately amplified.)

The new design proposes an available solid state laser with 700 W peak power, pulsed at 4 kHz, with 2000 shots per scan, 50 in elevation for each of 40 azimuth angles. The transmit angles are 1° apart in azimuth and 0.7° in elevation. The detectors have a field of view of 40° in azimuth and 21° in elevation. At the maximum planned vehicle speed of three meters per second and at two scans per second, the vehicle will travel 1.5 meters per scan. This allows five full scans to be completed between 10m and 2m of range, producing five views of a terrain feature from slightly different angles during an approach. The triangulation uncertainty is theoretically about 8% in range at 10 meters and about 2% at two meters. Elevation uncertainties are five times better at 10 meters and about the same at two meters. The receiver would use a linear array of 48 optical fibers, each terminated in a wideband photocell-amplifier, time gate, comparator, and latch. While some optical filtering may be useful, our experience suggests that it probably need be minimal, even in bright sunshine. The structure of a programmable timing module for controlling such a system is also described in reference [8].

SUMMARY

The first of the two objectives was to obtain detailed performance data on the ML/MD system currently in use. This system uses a pulsed laser diode and an eight-sided rotating mirror on a slowly rotating mast to scan the terrain in a 32 x 32 array once each mast revolution (about two seconds). A lens and 20 element linear photodiode array on the same mast, with 20 amplifiers, time gates, comparators, and latches serves as the detection scheme. Initial attempts to collect data indicated several deviations from expected results. These required some detailed analyses to confirm the calibration values, and some hardware troubleshooting and repair where necessary along with some improved software. Most of this is detailed in reference [6]. Most of the actual measurements on artificial terrain were done by Clement [7]. They show that the system, designed for a maximum range of three meters, only has a useful range in the laboratory of two meters, but that it does have sufficient resolution to reasonably insure the safety of a slow-moving vehicle in that both positive and negative obstacles are detected when their height approaches the radius of the wheels. Cross-path hazards were also reliably indicated. Ramp hazard detection was also investigated but the results were not quite so encouraging, although the basic difficulty is likely in the software. It is also clear that for some pitch angles, the field of view may be inadequate in the current system.

Our second objective was to design a similar system with extended range capability for use with a terrestrial vehicle with a maximum speed of about three meters per second. This design is documented by Hoogeveen [8]. The proposed system uses a more powerful laser fired at a higher rate, an elevation deflection system consisting of a set of holograms on a rotating disk, a galvanometer-driven mirror for deflection in azimuth, no rotating mast, a separately located receiver consisting of a cylindrical lens system or a galvanometric mirror and a group of optical fibers to distribute the light received to separate detectors and processors, all with a common electronic control system.

With a seven-fold increase in laser power and improvement in light sensitivity by at least 100, the theoretical range improvement is at least 25 times. This is because the received signal strength depends on the inverse square of the distance from the target back to the detector (as long as the entire transmitted beam is within the field of view of the detector as it is with a laser source). The azimuth resolution of the system is only sufficient to insure that a five cm. diameter post or tree trunk would be detected at about three meters. This may be marginal. No efforts have been made to attack the problem of distinguishing underbrush growth that is traversable from identical size rock outcroppings that may not be. Water hazards have also not been investigated.

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